Sea Ice Trends in the Antarctic and Their Relationship to Surface Air Temperature during 1979 to 2009

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Abstract

Surface air temperature (SAT) from four reanalysis/analysis datasets are analyzed and compared with the observed SAT from 11 stations in the Antarctic. It is found that the SAT variation from GISS (Goddard Institute for Space Studies) is the best to represent the observed SAT. Then we use the sea ice concentration (SIC) data from satellite measurements, the SAT data from the GISS dataset and station observations to examine the trends and variations of sea ice and SAT in the Antarctic during 1979 to 2009. The Antarctic sea ice extent (SIE) shows an increased trend during 1979-2009, with a trend rate of 1.36 ± 0.43% per decade. Ensemble empirical mode decomposition analysis shows that the rate of the increased trend has been accelerating in the past decade. Antarctic SIE trend depends on the season, with the maximum increase occurring in autumn. If the relationship between SIC and GISS SAT trends is examined regionally, Antarctic SIC trends agree well with the local SAT trends in the most Antarctic regions. That is, Antarctic SIC and SAT show an inverse relationship: a cooling (warming) SAT trend is associated with an upward (downward) SIC trend. It is also concluded that the relationship between sea ice and SAT trends in the Antarctic should be examined regionally rather than integrally.

1. Introduction

Satellite observed data show that Arctic and Antarctic sea ice extents (SIEs) have different trends since the 1970s (Cavalieri et al. 1997; Comiso and Nishio 2008). Arctic SIE decreases dramatically, and the rate of decline of summer SIE has been accelerating in recent years (Perovich and Richter-Menge 2009). Arctic sea ice retreats faster in summer than winter and this has been attributed to global warming (Serreze et al. 2007). But Antarctic SIE has a positive trend. As the time series become longer, the positive trend becomes significant (Cavalieri and Parkinson 2008).

Cavalieri et al. (1997) found that Antarctic SIE increased by 1.3 ± 0.2% per decade from November 1978 to December 1996. Zwally et al. (2002) also estimated that the trend of Antarctic SIE is 0.98 ± 0.37% per decade from 1979 to 1998. From 1979 to 2002, the trend of Antarctic SIE is 0.80% per decade (Cavalieri et al. 2003). A recent study (Turner et al. 2009) shows that the trend of Antarctic SIE during 1979-2006 is 0.97% per decade. Here we estimate Antarctic SIE trend during 1979-2009, and the result shows that the positive trend is larger with a rate of 1.36 ± 0.43% per decade.

Many studies examined Antarctic sea ice variations. These studies have shown that Antarctic sea ice is related to and/or controlled by the Southern Annular Mode (SAM), El Niño-Southern Oscillation (ENSO), oceanic conditions, ozone depletion, and other factors. SAM has a significant impact on regional Antarctic sea ice (Lefebvre et al. 2004; Lefebvre and Goosse 2005). When the SAM index is high, sea ice in the Weddell Sea and near the Antarctic Peninsula will decrease, but sea ice in the Ross and Amundsen Seas will increase. ENSO showed a teleconnected influence on Antarctic sea ice (Yuan 2004), which is featured with the Antarctic Dipole (an out-of-phase relationship between sea ice anomalies in the South Pacific and South Atlantic). Liu et al. (2004) pointed out that both the SAM and ENSO can affect Antarctic sea ice, but the magnitude of the ice changes associated with the SAM and ENSO is much smaller than that of the regional ice trend. Stratospheric ozone depletion is also argued to have an important role in the recent increase of Antarctic SIE (Tuner et al. 2009).

Steig et al. (2009) showed that continent-wide average near-surface temperature in the Antarctica has a positive trend over the past 50 years. Zhang (2007) also pointed out that Antarctic sea ice is increasing under warm atmospheric and oceanic conditions. Ocean-ice coupled model suggested the ice melting from ocean heat flux is decreased under warm atmospheric and oceanic conditions. This can explain why Antarctic sea ice has an increased trend under warm conditions.

It seems that Antarctic sea ice and surface air temperature (SAT) have a complicated relationship. The purpose of this paper is to investigate the relationship. The present paper makes several contributions. First, the paper analyzes SAT variations of four datasets, compares them with station observations in the Antarctic, and evaluates these four datasets in the Antarctic region. It is concluded that SAT in the GISS (Goddard Institute for Space Studies) dataset agrees best with station observations. Second, this study shows that the Antarctic sea ice concentration (SIC) trends agree well with the GISS SAT trends. If we take the Antarctic as a whole, we can find that SIE has a positive trend, and SAT also has a positive trend as noticed by Zhang (2007). But if we examine SIC trends and SAT trends regionally and seasonally, we find that most of the Antarctic SIC and local SAT trends have an inverse relationship. Based on sea ice thermodynamics, Antarctic sea ice trends and SAT trends should have a close relationship. But there are few studies investigating the Antarctic sea ice and SAT trends. One possible reason may be that some SAT datasets have large error in the Antarctic and thus it is difficult to study the relationship between sea ice trends and SAT trends. Third, both SIE and SAT in the Antarctic show seasonal variations. SIE has the largest trend in austral autumn (in this paper, the season always refers to the austral season), and the largest SAT trend also occurs in autumn.

2. Datasets

Monthly SIC data with a horizontal resolution of 25×25 km are used in this study. The SIC dataset is derived from Nimbus-7 SMMR and DMSP SSM/I passive microwave data by NASA. The dataset is provided by the National Snow and Ice Data Center (Cavalieri et al. 1996; Meier et al. 2006).

Four monthly SAT reanalysis/analysis datasets from GISS (Hansen et al. 2010), NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) (Kalnay et al. 1996), COREs (Common Ocean-ice Reference Experiments) (Large and Yeager 2009) and ECMWF (European Center for Medium range Weather Forecasting) are compared with observed SAT from 11 stations in the

Antarctic. The datasets of NCEP/NCAR, COREs and ECMWF are reanalyzed data based on data assimilation and numerical models, whereas the GISS dataset is based on interpolation and extrapolation of observations. The standard GISS analysis interpolates among station measurements and extrapolates anomalies as far as 1200 km into regions without measured stations (Hansen et al. 2010). Note that COREs SAT in this study is from January 1979 to December 2006. ECMWF SAT in this study includes two datasets: ECMWF 40-year Re-Analysis (ERA-40) and ECMWF Interim Re-Analysis (EIRA). ERA-40 SAT from January 1979 to August 2002 and EIRA SAT from September 2002 to December 2009 are used. The observed SATs from 11 stations are used to assess the four reanalysis SAT datasets, and also used to analyze the relationship between SAT and SIC. Detailed information about these 11 stations is given in Figure 1 and Table 1. The 11 station SAT observations are provided by British Antarctic Survey. In this study, all anomalies of SAT, SIC and SIE are defined as the deviation from the corresponding mean annual cycle from 1979 to 2009. COREs SAT anomaly is an exception, which is defined as the deviation from the corresponding mean annual cycle from 1979 to 2006. Wu et al. (2008) provided another definition of anomaly with respect to modulated annual cycle. This definition may potentially lead to a more effective way to understand and predict climate variability. However, for the reason of making direct comparison of our estimation of trends of SIE, SIC and SAT and these of previous studies, we use traditional definition.

We first compare four SAT reanalysis datasets with available station observations.

Figure 2 shows the zonal mean linear trends of annual-mean SAT during 1979-2009 for the four SAT datasets. In most regions of the globe, SAT has increased since 1979. The Northern Hemisphere has larger increased trends than the Southern Hemisphere, and the polar regions have large increased trends in comparison with other regions. The Antarctic is special because the SATs show large differences. In particular, the NCEP/NCAR reanalysis Antarctic SAT has a large increased trend during the past 30 years as in the Arctic. The largest trend in the Antarctic can reach 0.14°C per year. COREs SAT is the adjusted version of the NCEP/NCAR reanalysis dataset, but in the high latitude SAT is adjusted based on in situ observations (Large and Yeager 2009). Thus, Figure 2 shows that the difference between the COREs and NCEP/NCAR occurs mainly in the polar regions. The lack of observational data in high latitude makes the NCEP/NCAR SAT trend in the Antarctic be unrealistic. This is also noticed by Johanson and Fu (2007) who pointed out the overestimation of trend in the Antarctic region from the NCEP/NCAR reanalysis.

The other three SAT datasets also show different trends in the Antarctic region. In order to validate these reanalysis datasets, we compare SAT trends of these reanalysis/analysis fields with station observed SAT trend in autumn (March, April and May) during 1979-2009 (Figure 3). Observation shows that SATs in stations 1, 2, 6, 7 and 8 have increased trends, whereas SATs in stations 3, 4, 5, 9, 10 and 11 have decreased trends. However, almost all of SAT trends from COREs, NCEP/NCAR and ECWMF datasets are positive (except for COREs SAT trends of station 11). This indicates that

SATs from these three datasets in the Antarctic region have large errors. On the other hand, the GISS SAT trends agree well with the station observed trends although the trend amplitudes are different. Thus, the subsequent analyses will focus on the GISS reanalysis dataset and 11 station observations.

3. Antarctic sea ice and SAT variations

3.1 Antarctic SIE trends during 1979-2009

As stated in the introduction, Arctic and Antarctic SIEs have different trends. SIE in the Arctic shows a decreased trend, whereas SIE in the Antarctic has an increased trend. Figure 4 shows the Antarctic SIE anomaly and its trend during the past 30 years. Here SIE is calculated as the sum of the area where SIC exceeds 15%. One can see that Antarctic SIE has an upward trend since 1979. During 1979-2009, the positive linear trend is 1.36 ± 0.43% per decade (± 0.43% is 95% confidence interval of the linear trend).

To further examine the trend, we use a recently developed method called the Ensemble Empirical Mode Decomposition (EEMD) (Huang et al. 1998; Wu and Huang 2009). Based on the EEMD analysis, the Antarctic SIE secular trend (nonlinear) is obtained. EEMD analysis also shows the positive trend of Antarctic SIE since 1979 (Figure 4). The rate of the positive trend has been accelerating in the past decade. Before 2000 EEMD trend is smaller than linear trend, but after 2000 EEMD trend exceeds linear trend gradually. As other data analysis methods, EEMD method also has some sensitivity to data ends, but our tests show that the sensitivity to the data ends does not change the conclusion that the secular trend is accelerating. The accelerating rate of the positive SIE trend does not support the hypothesis that increasing Antarctic SIE is linked to stratospheric ozone depletion (Tuner et al. 2009) since the ozone has been recovering after the Montreal Protocol (September 16, 1987) that banned ozone depleting chemicals.

As discussed by Turner et al. (2009) and Cavalieri et al. (2008), Antarctic SIE trend has seasonal variation. Figure 5 shows that monthly and seasonal Antarctic SIE trends during 1979-2009 are both positive. The largest monthly trend occurs in March, with an increased rate of 5.04% per decade. Generally, the Antarctic SIE trends in summer and autumn (from December to May) are larger than those in winter and spring (from June to November). Of the four seasons, SIE trend in autumn is the largest with a rate of 3.19% per decade.

3.2 Antarctic SIC trends during 1979-2009

The spatial distributions of the Antarctic linear SIC trend for four seasons are shown in Figure 6. Antarctic SIC trends in spring and winter share a similar spatial pattern, and the same is true in summer and autumn. In spring and winter, SIC in the Bellingshausen Sea, the Weddell Sea and part of the western Pacific Ocean has a decreased trend. SIC in other regions has a positive trend, with the positive trend being prominent in the Ross Sea.

In summer and autumn, most regions of the Antarctic show an positive SIC trend.

However, the SIC in the Bellingshausen Sea, the Amundsen Sea and near the Antarctic Peninsula has a decreased trend.

3.3 Relationship between Antarctic SIC and SAT trends

In the past 50 years, the spatial complexity of SAT change has occurred across the Antarctic (Turner et al. 2005). Turner et al. (2005) studied 19 stations that observed SAT, and showed that 11 of these stations had warming trends and 7 of these stations had cooling trends in the past 50 years. Johason and Fu (2007) pointed out that satellite observed Antarctic tropospheric temperature has cooled in summer and autumn since 1979, and warming prevails in winter and spring.

We have examined GISS SAT trends during 1979-2009. Figure 7 shows the linear trends for four seasons. Antarctic SAT has different trends in different regions. SAT in the Bellingshausen Sea, the Amundsen Sea and near the Antarctic Peninsula has warming trends all year long, and in autumn and winter the warming trends are more obvious. The maximum warming trend can reach 0.08°C per year. In summer and autumn, a cooling trend is dominated except for the regions that have year long warming trends. The same as SIE, SAT has the largest trend in autumn. The largest warming trend and the largest cooling trend both occur in autumn.

A comparison of Figure 7 and Figure 6 shows that the Antarctic SIC trends agree well with the GISS SAT trends, especially in summer and autumn. The decreased trends of SIC in the Bellingshausen Sea, the Amundsen Sea and near the Antarctic Peninsula are consistent with the SAT warming trends in these regions. At the same time, the increased trends of SIC in the Ross Sea, the Weddell Sea, the Indian Ocean sector and the western Pacific Ocean sector agree well with the SAT cooling trends in these regions during summer and autumn.

In order to clearly illustrate the relationship between SAT and SIC, the product of SAT and SIC linear trends is calculated and shown in Figure 8. The product in most Antarctic regions is negative, indicating that a warming (cooling) trend of SAT is associated with a decreased (increased) trend of SIC. In other words, SAT and SIC trends have an inverse relationship. The product has maximum absolute value in autumn. This also suggests that SAT and SIC have large changes in autumn. Not only SAT and SIC trends but also SAT and SIC anomalies have the inverse relationship as shown by the correlation maps in Figure 9.

The relationship between SIC and SAT in the Antarctic is further examined and confirmed by using the observed SAT from the 11 stations. Since SAT and SIC have the largest changes in autumn, we plot the SAT and local SIC anomalies in autumn for all 11 stations (Figure 10). Generally, local SIC variations agree well with those of SAT. When SAT anomaly is high (low), SIC is anomalously low (high). In order to quantitatively illustrate the relationship between SIC and SAT, Table 2 shows the correlation coefficients between SIC and SAT from 11 stations and their linear trends in autumn. One can see that 6 of these 11 stations have cooling trends and 5 of these stations have warming trends. Station 11 has the largest cooling trend and station 6 has the largest warming trend. Except for stations 6 and 8, all other 9 stations show a significantly negative correlation between SIC and SAT.

If we examine the relationship between sea ice trends and SAT trends regionally, we can find that SIC trends and local SAT trends have an inverse relationship over most regions of the Antarctic. But if the relationship is examined integrally and averagely, both the integrated SIE and the averaged SAT over the Antarctic have positive trends (Figure 2 and Figure 4). This means that the reverse relationship will be masked by integral and average. To clearly demonstrate this point, we use stations 2, 7, and 10 as an example. The products of SAT trends and SIC trends for stations 2, 7 and 10 are all negative (Table 2), indicating that the inverse relationship exists for these 3 stations. But if we calculate the averaged SAT and integrated SIE for the 3 stations, we can get warming SAT trend and positive SIE trend. Therefore, it is concluded that the relationship between sea ice and SAT trends should be examined regionally rather than integrally.

4. Summary

The present paper uses the monthly SIC data from Nimbus-7 SMMR and DMSP SSM/I passive microwave data to show that Antarctic SIE has an increased trend in the past 30 years (1979-2009). The increased trend is about 1.36 ± 0.43% per decade. The rate of Antarctic SIE positive trend has been accelerating in the past decade. Antarctic SIE trend shows a large seasonal variation, with larger trend in summer and autumn. SIC trends have a similar spatial pattern in spring and winter, and a similar pattern in summer and autumn. SIC in the Bellingshausen Sea, the Amundsen Sea and near the Antarctic Peninsula has a downward trend, whereas it has an upward trend in the Ross Sea, the Weddell Sea, the Indian Ocean sector and the western Pacific Ocean sector.

The four SAT datasets show large differences of SAT trend in the Antarctic region. Our analyses and comparison with the observed SAT from 11 stations suggest that among the four datasets, the GISS SAT should be the most reliable one for studying the SAT variation in the Antarctic.

The SAT and SIC trends illustrate an inverse relationship in most of the Antarctic regions, especially in summer and autumn. This indicates that a cooling (warming) SAT trend is associated with an upward (downward) SIC trend in the Antarctic. The station observations also confirm the inverse relationship between SAT and SIC. In most of the Antarctic regions, a cooling trend of SAT in summer and autumn is associated with an increased trend of SIC.

Our analyses show that the relationship between sea ice and SAT trends should be examined regionally rather than integrally. Although SIC trend in most regions is consistent with the regional SAT trend in the Antarctic, there are some regions where SIC trend is not consistent with SAT trend. The reason is not clear now. Previous studies suggest that oceanic processes such as the weakened ocean stratification and ocean heat transport under the ice may cause this (Zhang 2007). Obviously, this topic needs to be further studied in the future.

Acknowledgments:

SIC data is provided by http://nsidc.org/data/nsidc-0051.html, GISS SAT data is available from http://data.giss.nasa.gov/gistemp/, NCEP/NCAR reanalysis SAT data is from http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html, COREs SAT data is provided by http://data1.gfdl.noaa.gov/nomads/forms/mom4/COREv2.html, and ECMWF SAT data is available from http://data.ecmwf.int/data/, 11 stations SAT data are download from http://www.antarctica.ac.uk/met/gjma/. The authors thank the above data providers. This study is supported by 973 Project (No. 2010CB950303; No. 2010CB950502) and the Key Project of National Natural Science Foundation of China (No. 40730842).

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Figure and Table Captions

Figure 1. Locations and names of the 11 observed stations.

Figure 2. Zonal mean linear trends of annual-mean SAT during 1979-2009 from four SAT datasets

Figure 3. Linear trends (1979-2009) of autumn SAT in the 11 observed stations in comparison with those of four SAT datasets.

Figure 4. SIE anomaly and trends in the Antarctic during 1979-2009.

Figure 5. Monthly (a) and seasonal (b) Antarctic SIE trends during 1979-2009 (unit: % per decade).

Figure 6. Linear trends (unit: % per year) of the Antarctic SIC in (a) spring, (b) summer, (c) autumn and (d) winter during 1979-2009.

Figure 7. Linear trends (unit: °C per year) of the GISS SAT in (a) spring, (b) summer, (c) autumn and (d) winter during 1979-2009.

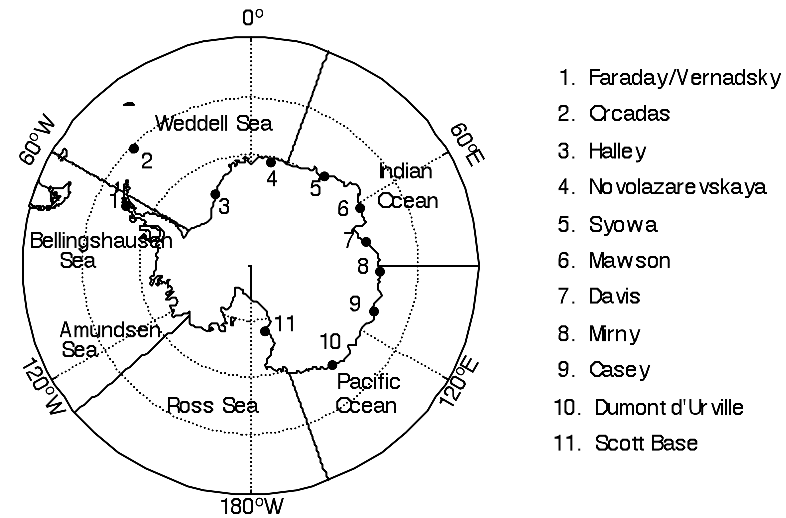
Figure 8. The product of SAT and SIC linear trends in (a) spring, (b) summer, (c) autumn and (d) winter during 1979-2009.

Figure 9. The correlation of SAT and SIC anomalies in (a) spring, (b) summer, (c) autumn and (d) winter during 1979-2009.

Figure 10. The variations of local SIC and SAT anomalies in autumn during the past 30 years. The SAT data are from the 11 station observations.

Table 1. Information about the 11 stations.

Table 2. Correlation coefficients between SIC and SAT, their linear trends and the product sign of SAT and SIC trends for the 11 stations in autumn.



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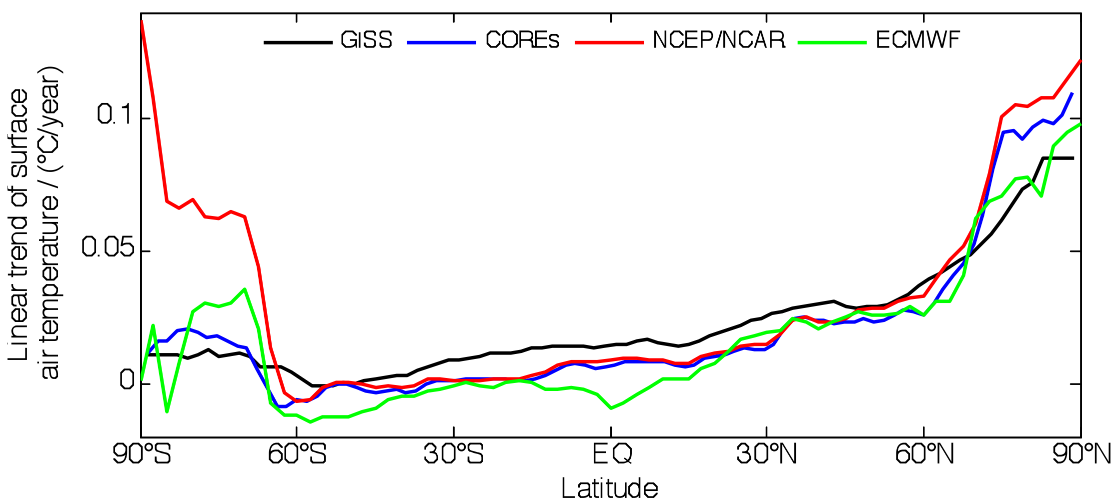

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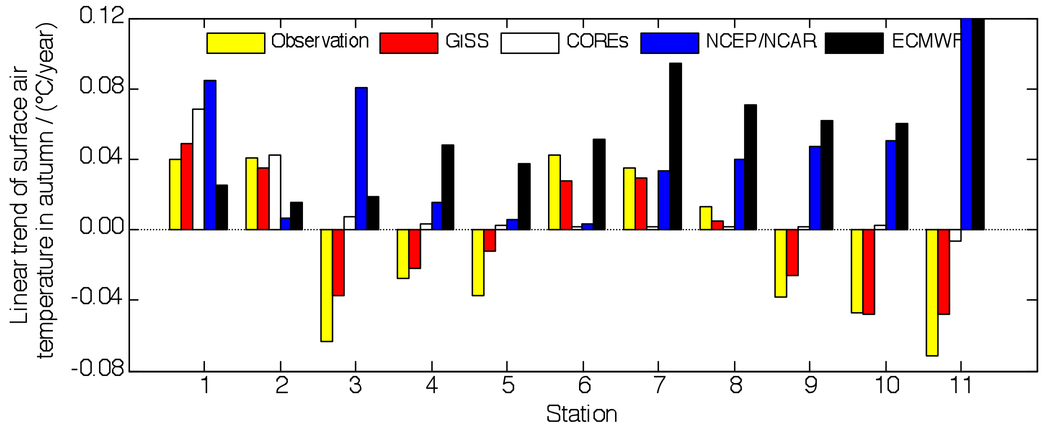

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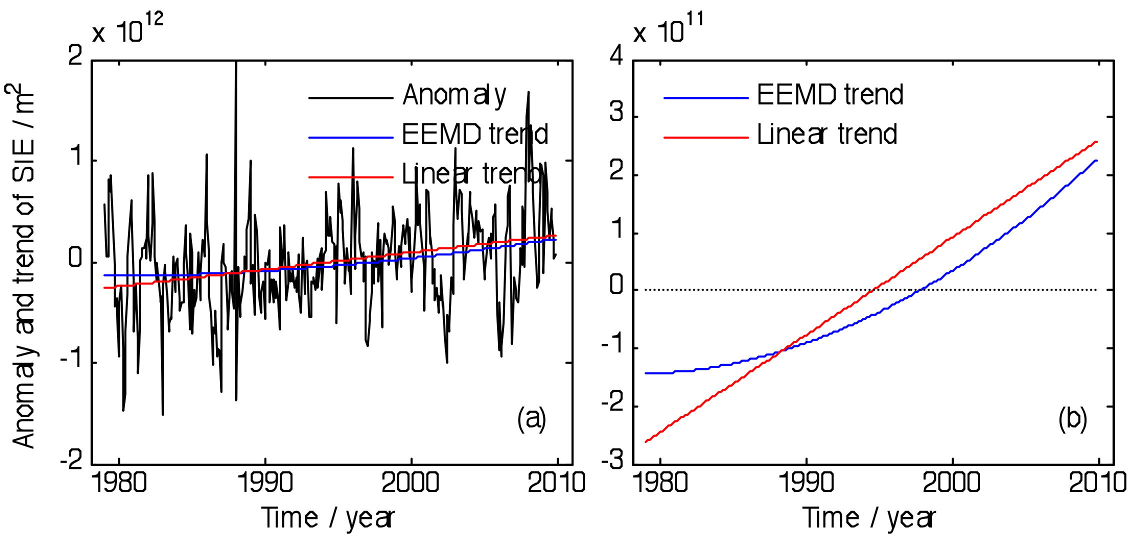

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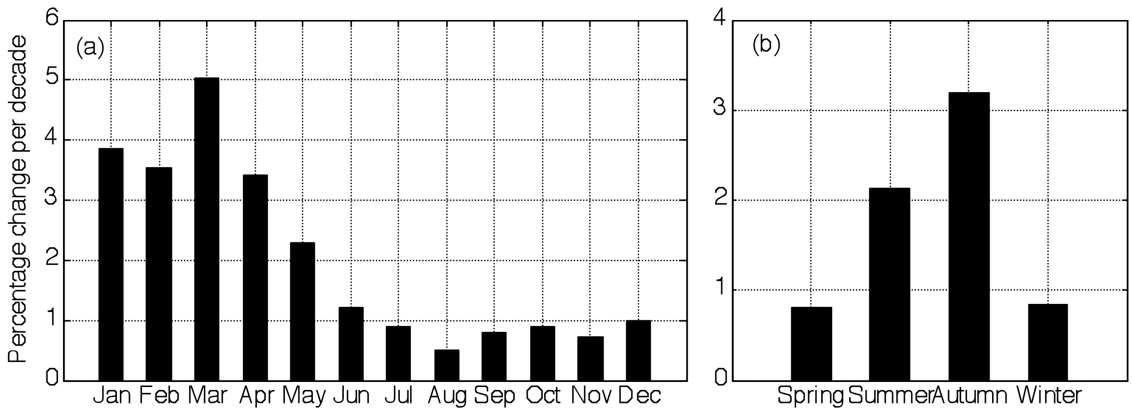

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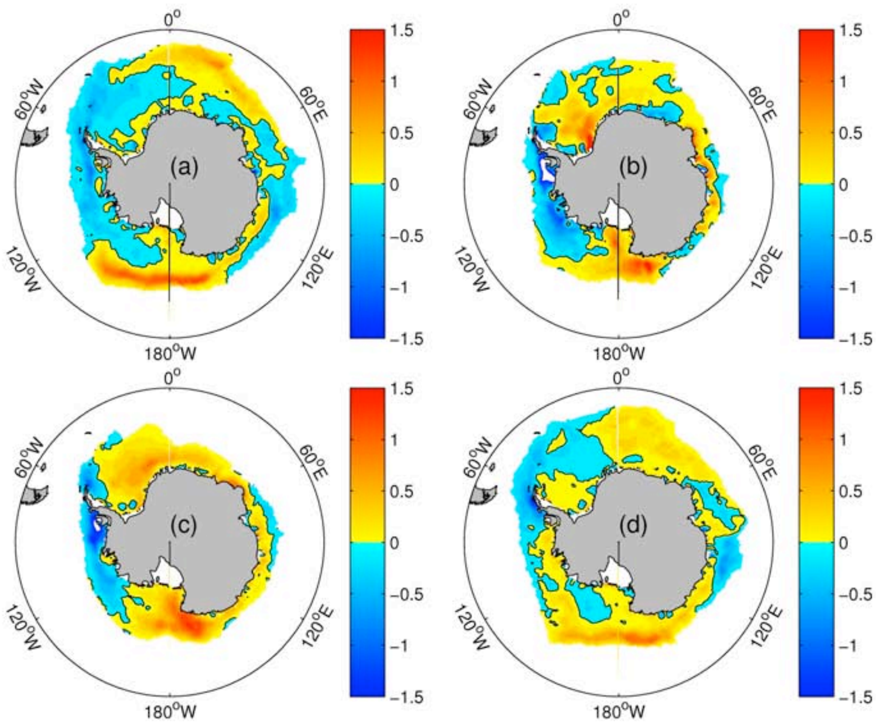

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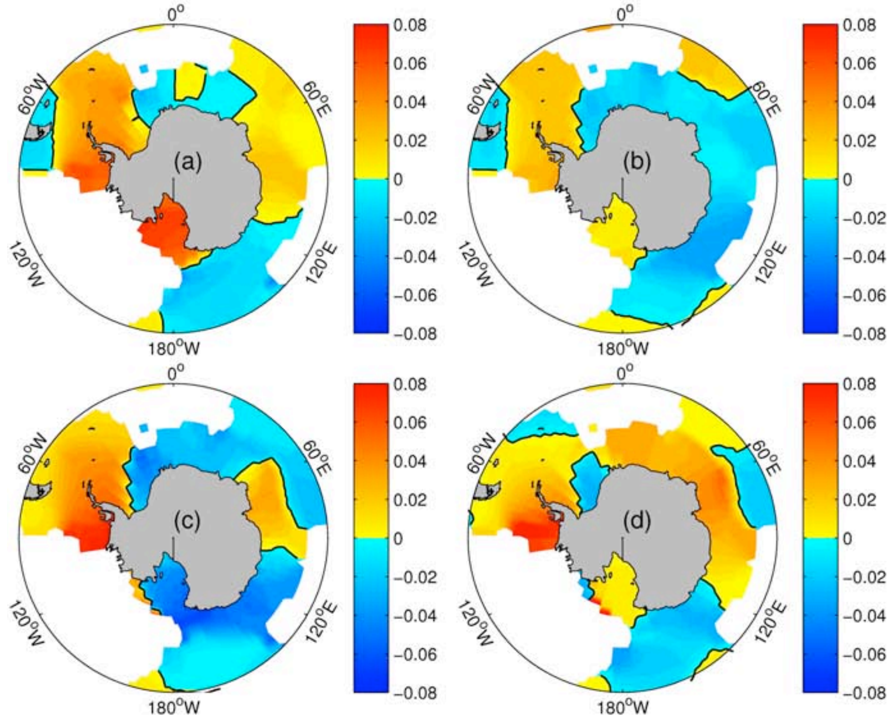

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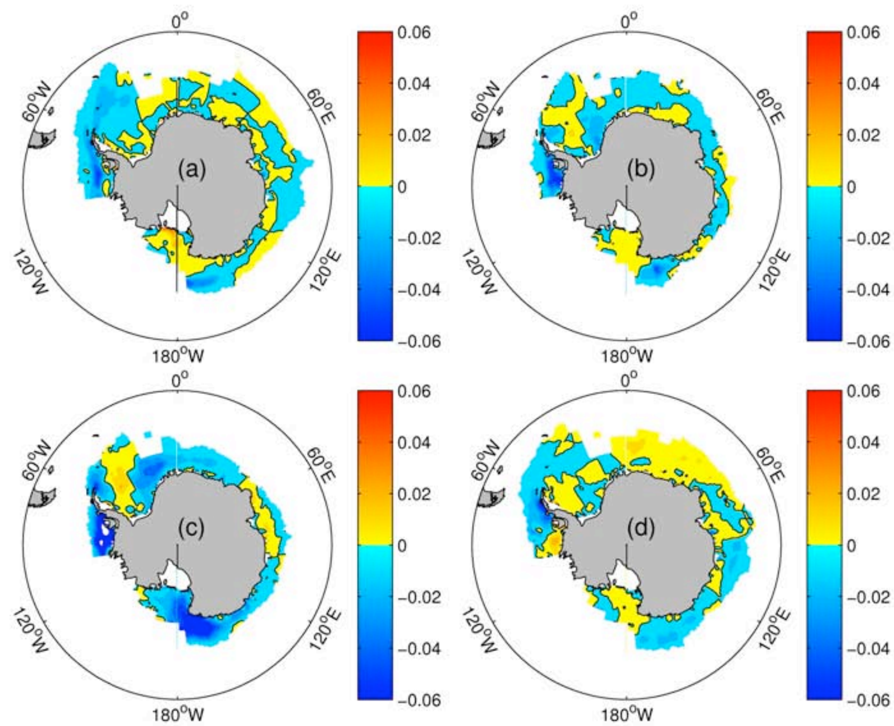

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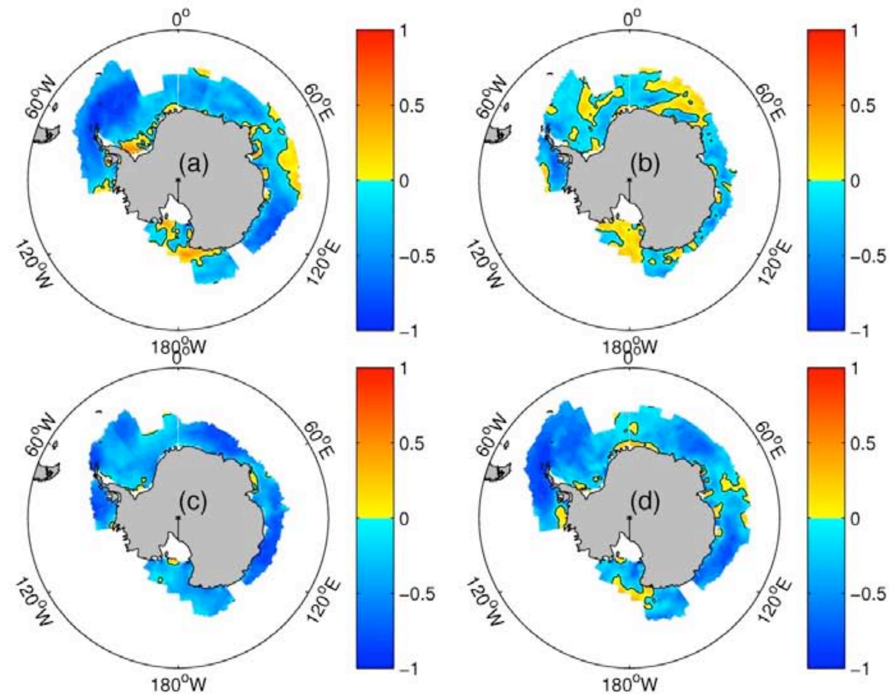

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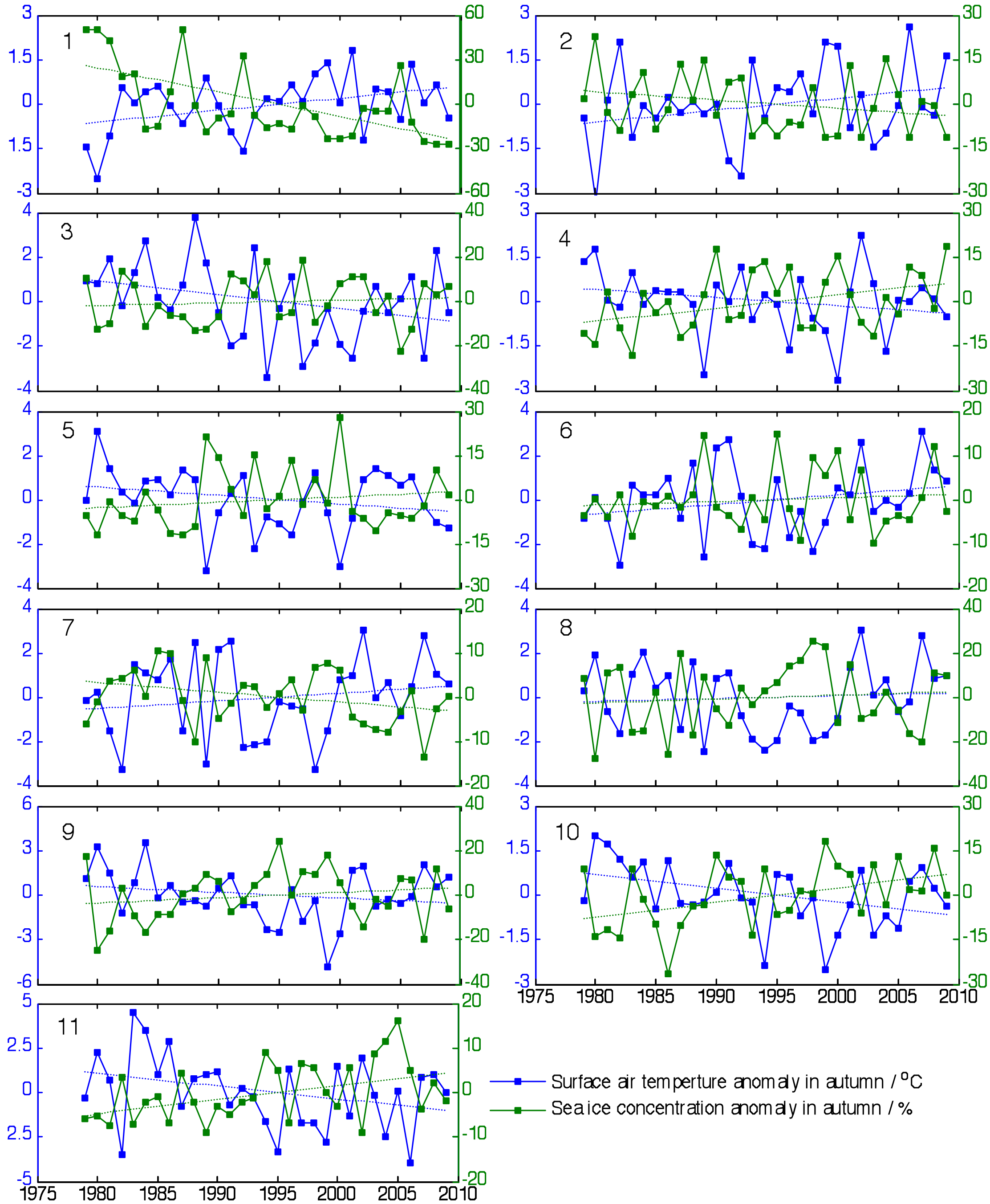

Figure 10. The variations of local SIC and SAT anomalies in autumn during the past 30 years. The SAT data are from the 11 station observations.

Table 1. Information about the 11 stations.

Station No.	Station name	Longitude	Latitude	Country
1	Faraday/Vernadsky	64°16'W	65°15'S	Ukraine
2	Orcadas	44°43'W	60°45'S	Argentina
3	Halley	26°30'W	75°35'S	British
4	Novolazarevskaya	11°50'E	70°46'S	Russia
5	Syowa	39°35'E	69°00'S	Japan
6	Mawson	62°52'E	67°36'S	Australia
7	Davis	77°58'E	68°35'S	Australia
8	Mirny	93°01'E	66°33'S	Russia
9	Casey	110°32'E	66°17'S	Australia
10	Dumont d'Urville	140°00'E	66°40'S	France
11	Scott Base	166°46'E	77°51'S	New Zealand

Table 2. Correlation coefficients between SIC and SAT, their linear trends and the product sign of SAT and SIC trends for the 11 stations in autumn.

Station name	Correlation coefficients	Confidence level	SAT linear trends (℃ /decade)	SIC linear trends (%/decade)	The product sign
Faraday/Vernadsky	-0.70	99%	0.40	-16.32	-
Orcadas	-0.76	99%	0.41	-2.79	-
Halley	-0.59	99%	-0.63	1.18	-
Novolazarevskaya	-0.51	99%	-0.27	4.45	-
Syowa	-0.78	99%	-0.38	1.87	-
Mawson	-0.01	——	0.42	0.78	+
Davis	-0.46	95%	0.35	-2.20	-
Mirny	-0.60	99%	0.13	1.76	+
Casey	-0.76	99%	-0.38	2.33	-
Dumont d'Urville	-0.57	99%	-0.47	5.04	-
Scott Base	-0.62	99%	-0.71	3.21	-